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DETERMINATION OF PHYSICAL CHARACTERISTICS OF SURFACE SOIL LAYER ACCORDING TO RADIO THERMAL EMISSION

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16. Abstract

A method of determining the physical characteristics of various soils on the basis of radio thermal emission is described. Conclusions are made on the basis of numerical experiments for real temperature and humidity profiles. Radio brightness temperature is a function of surface temperature and emissivity of soil. It is possible to determine the temperature profile constant at great depths and the surface temperature gradient. The effects of foam and organic films on the radio emission of the ocean surface are discussed.

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DETERMINATION OF PHYSICAL CHARACTERISTICS OF SURFACE SOIL LAYER ACCORDING TO RADIO THERMAL EMISSION

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Indirect methods are used extensively at the present time for determining /342* the physical characteristics of the atmosphere-earth system. In particular, passive radar methods are based on interpretation of measurement data of the thermal radiation of the atmosphere and underlying surface for the purpose of obtaining information about their physical properties. The centimeter wavelength band is most important for the purpose of remote sensing of the soil, and it is in this connection that: 1) the atmosphere is practically transparent to the radiation of the soil in this band, permitting remote measurement of its radiation (radio brightness temperature T_b); 2) the radiation of the soil is formed in some sufficiently extensive layer. Therefore it is theoretically possible to extract from measurements of the radio brightness temperature on several wavelengths information about the physical properties of this layer that influence radiation.

The radio brightness temperature T_b of soil, measured in the normal direction, is determined by the following equation

$$T_b = \Sigma(w)\int_0^\infty \alpha(w, z)\, T(z) \exp\left(-\int_0^z \alpha(z', w)\, dz'\right) dz, \tag{1}$$

where $\Sigma(w)$ is the emissivity of the soil, $\alpha(w, z)$ is the absorption coefficient, $T(z)$ is the temperature profile, w and z are the humidity of the soil and vertical coordinate, respectively.

The emissivity of soil depends both on its properties (composition of the soil, its electrical parameters, features of their distribution with depth), and also on the characteristics of the interface (smoothness or roughness, the presence of covers, etc.). For a smooth surface or for a surface with a

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*Numbers in the margin indicate pagination in the foreign text.

roughness element with a radius much larger than wavelength, the radiation coefficient can be determined through the mirror reflection coefficient R(w):

$$\Sigma(w) = 1 - |R(w)|^2. \qquad (2)$$

We derived expressions for the reflection coefficients of soil that is linearly inhomogeneous through depth. Analysis of these expressions revealed that the influence of heterogeneity on the radiation coefficients of real soils is not great and the reflection coefficients of soil can be calculated in the first approximation using the Fresnel equations (the effect of inhomogeneity is considerable only at long wavelengths of the order of 60 cm for soils with a dry surface). The radiation coefficient is determined by the real dielectric constant ε of the medium, which in the case of sand and clay increases linearly with humidity, just like the absorption coefficient [1].

Thus the radio brightness temperature of soil is a functional both of temperature and of humidity. Therefore, in the general case of remote sensing problems it is necessary to analyze both the humidity characteristics and the temperature conditions of the soil.

TABLE 1 /343

Type of surface	Brief description	λ, cm	Σ
Sand	River, dry, medium coarse; level surface,	1.6	0.933
	25 cm thick layer	0.8	0.939
Sand	River, wet, level surface, 25 cm thick	3.2	0.749
	layer	1.6	0.769
Sand	River		
	humidity w = 3.4%	3.2	0.927
	" w = 10%	3.2	0.703
	" w = 14.5%	3.2	0.655
Sand	Dry, dusty	3.2	0.884
Rocky	Coarse limestone, 25 cm thick layer	3.2	0.877
Grass cover	Arid, height of grass 15-20 cm, thickness	3.2	0.935
	of top soil 20 cm	1.6	0.961
Grass cover	Wet, height of grass 15-20 cm, thickness	3.2	0.890
	of top soil 20 cm		
Snow cover	Level surface, density 0.58 g/cm^3	0.8	0.944

The possibilities of solving the special problem of determination of soil temperature at a known humidity are discussed in [2, 3]. It was found that for a radio brightness temperature measurement error of 0.5°K it is possible to reconstruct the temperature profile with sufficient accuracy (1-3°). In order to solve the problem of reconstructing the temperature profile of soil either independent determination of humidity with an accuracy of the order of 1%, or the combined solution of the problem of reconstructing the temperature and humidity characteristics is essential.

In the combined statement of the problem of variation of radio brightness temperature δT_b are determined by changes of all variable parameters of equation (1):

$$\delta T_b \approx A_\Sigma \delta\Sigma(w_0) + A_T \delta T + A_w \delta w. \qquad (3)$$

In order to evaluate δT_b and the influence of the unknown parameters of the physical state of soil, we derived an analytical expression for the radio brightness temperature of a layer of soil with linear change of temperature and humidity through depth and in which the temperature levels off to a constant value at some depth:

$$T_b \approx \Sigma\left\{T_0 + \frac{\overline{dT}}{dz}\exp\left(\frac{\alpha_0}{2a}\right)^2 \times \left[\frac{\alpha_1}{a}\Phi\left(1/2, 3/2, -\frac{\alpha_1^2}{2a}\right) - \frac{\alpha_0}{a}\Phi\left(1/2, 3/2, -\frac{\alpha_0^2}{2a}\right)\right]\right\}, \qquad (4)$$

where T_0 is the surface temperature of the soil, which may be determined on the basis of infrared measurement data; $\overline{dT}/dz$ is the mean temperature gradient, α_0 and α_1 are the absorption coefficients of the soil at the surface and at the depth where the temperature of the soil may be assumed constant; a is the absorption coefficient gradient; $\Phi(1/2, 3/2, x)$ is a degenerate hypergeometric function.

Analysis of expression (4) indicates that the possibility of reconstructing humidity characteristic depends on the nonisothermicity of the temperature profile. In the case of isothermicity, obviously, it is possible to determine only the humidity of the near-surface layer, which determines the emissivity of soil [4].

In the limiting cases of large (centimeter waves) and small (decimeter waves) parameters $\alpha_0^2/(2a)$ and $\alpha_1^2/(2a)$ we have

$$T_b \approx \begin{cases} \Sigma(T_0 + T'/\alpha_0), & \alpha_0^2, \alpha_1^2/(2a) \gg 1, \qquad (5) \\ \Sigma T_\infty, & \alpha_0^2, \alpha_1^2/(2a) \ll 1, \qquad (6) \end{cases}$$

where T' is the surface temperature gradient, T_∞ is the temperature constant at great depths. It should be pointed out that approximation of the humidity profile by an exponent leads to the same limiting cases. /344

Numerical experiments for several real temperature and humidity profiles confirmed the data from "model" calculations and led to the following conclusions:

1. The radio brightness temperature of soil depends most strongly on the surface temperature and emissivity of the soil, which is determined by the near-surface humidity. Thus, for example, variations of T_b due to a change of humidity from 3 to 8% reached 30-40°, depending on wavelength, whereas contrasts T_b as a result of change of the deep humidity or temperature profiles of the soil are an order of magnitude smaller.

2. In the case of independent determination of T_0 (on the basis of infrared radiation, for example) and of Σ in the decimeter band it is possible to determine the temperature profile constant at great depths T_∞ and, in the centimeter band, to evaluate temperature gradient T' at the surface.

Since the method of remote surface temperature measurements is known we will examine briefly the problem of determining emissivity. A method of laboratory measurements of emissivity, which makes it possible to measure the radiation coefficients of the various surfaces under strictly controlled conditions [5], was developed for analyzing the dependence of the radio emission of natural surfaces on their state, temperature and humidity. The radiation coefficients of soil specimens were measured under laboratory conditions for various temperatures and humidities and the results were compared with the calculations.

The theoretical curves of emissivity of sand and clay as a function of humidity, determined according to the method described above, are presented in Figure 1. As is seen in Figure 1, the emissivity of sand is a strongly varying property. When the humidity increases from 3 to 15% the emissivity decreases from 0.93 to 0.65. The total water capacity of sandy podzolic soils, as is known, is about 20-25%, and the corresponding emissivity on the 3.2 cm wavelength is 0.61. Thus both the experiment and calculation indicate a strong dependence of the natural radiation of sand on its humidity and the radio brightness temperature contrasts due to a change of emissivity amount to several tens of degrees.

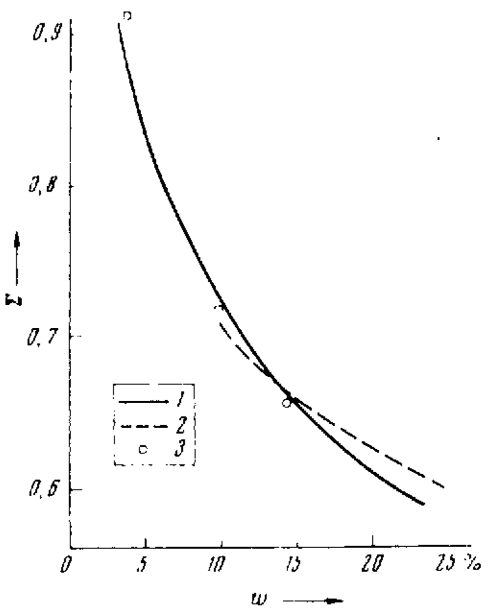

Figure 1. Emissivity as Function of Humidity on 3.2 cm Wavelength: 1, sand; 2, clay; 3, experimental values for sand.

The radiation properties of various real soil covers (Table 1) were analyzed in the 0.8-3.2 cm wavelength band for the purpose of investigating the possibility of remote indication of top soil characteristics. The emissivity data in this table were obtained by averaging many uniform /345 measurements. The measurements revealed that the emissivity of the investigated specimens varied considerably. The dependence of Σ on wavelength λ was also analyzed for wet and dry sand and it was found that reflection increases as wavelength increases. The effect of humidity is the same on all wavelengths: the emissivity of soil decreases as humidity increases. Measurements of the radiation coefficients of two forms of dry sand, one moderately coarse and one dusty, revealed that the emissivities are 0.93 and 0.88, respectively. Thus there is some variation in emissivity, apparently related to the structural difference of the selected specimens.

Recent analyses indicate that the formation of foam and organic films has an effect on the radio emission of the ocean surface. On the basis of the contribution of foam to radio emission it is possible to determine the parameters of wind wave action, and on the basis of the change of the radio brightness temperature of the sea as a result of the formation of films of petroleum products it is possible to determine the extent of pollution of the ocean surface. Laboratory measurements of specimens of foam, films of kerosene and oil on the surface of water were done in order to determine the effect of foam and organic films on radio emission. The radio brightness temperature of a water surface coated with films of kerosene and oil increased by 10-30°K, and when specimens of manmade foam are applied on the water surface this increment reaches 140-150°K during measurements on the 3.2 cm wavelength.

Thus, experimental investigation of the emissions of various types of underlying surfaces verified the theoretical conclusions concerning the promises of measurement of top soil characteristics by remote methods using radar and thermal sounding techniques.

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